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National Center for Earthquake Research
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OPEN FILE REPORT

PRELIMINARY INTERPRETATION OF AEROMAGNETIC AND GRAVITY DATA NEAR THE LARGE APERTURE SEISMIC ARRAY, MONTANA*

by

Isidore Zietz**, Carter Hearn**
and Donald Plouff***

1968

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ABSTRACT

Aeromagnetic and gravity maps of part of eastern Montana indicate the existence of several distinct crustal units whose influence must be considered in the interpretation of seismic data recorded at the Large Aperture Seismic Array. The magnetic map suggests the area contains 5 major crustal units separated by fault-like boundaries. The principal features of the gravity map are a marked high over the Porcupine dome, and a 40- by 70-mile gravity low to the northeast of Porcupine dome.

INTRODUCTION

The U. S. Geological Survey conducted aeromagnetic and gravity investigations near Miles City, Montana, (Fig. 1) to study the nature of the earth's crust and upper mantle in an attempt to explain the anomalous seismic travel times which have been observed in the vicinity of the Large Aperture Seismic Array (LASA). These investigations complement a seismic-refraction survey described by Borcherdt and Roller in an unpublished report submitted to the Advanced Research Projects Agency as Technical Letter NCER-2, in May 1967.

FIELD SURVEYS

The aeromagnetic survey covers a rectangular area bounded approximately by latitudes 44°30'N and 48°00'N and by longitudes 104°W and 110°W. Flight lines were flown at an altitude of 6,000 ft barometric along parallels of latitude at every five minutes of latitude. Several lines were flown normal to the flight lines to insure adequate control. Magnetic contour maps of the area were prepared at scales of 1:500,000 and 1:2,500,000 (Figs. 2 and 3). The large-scale map has a 20-gamma contour interval, and the regional field has not been removed. The small-scale map has a 100-gamma contour interval, and the earth's main field has been removed using Coast and Geodetic Survey data supplied by Nelson and Webber (personal communication). Flying was done in the summers of 1966 and 1967.

Gravity observations were made over an area slightly larger than the area covered by the outermost elements of the LASA array (Fig. 4). A total of 1,153 gravity stations was established in an

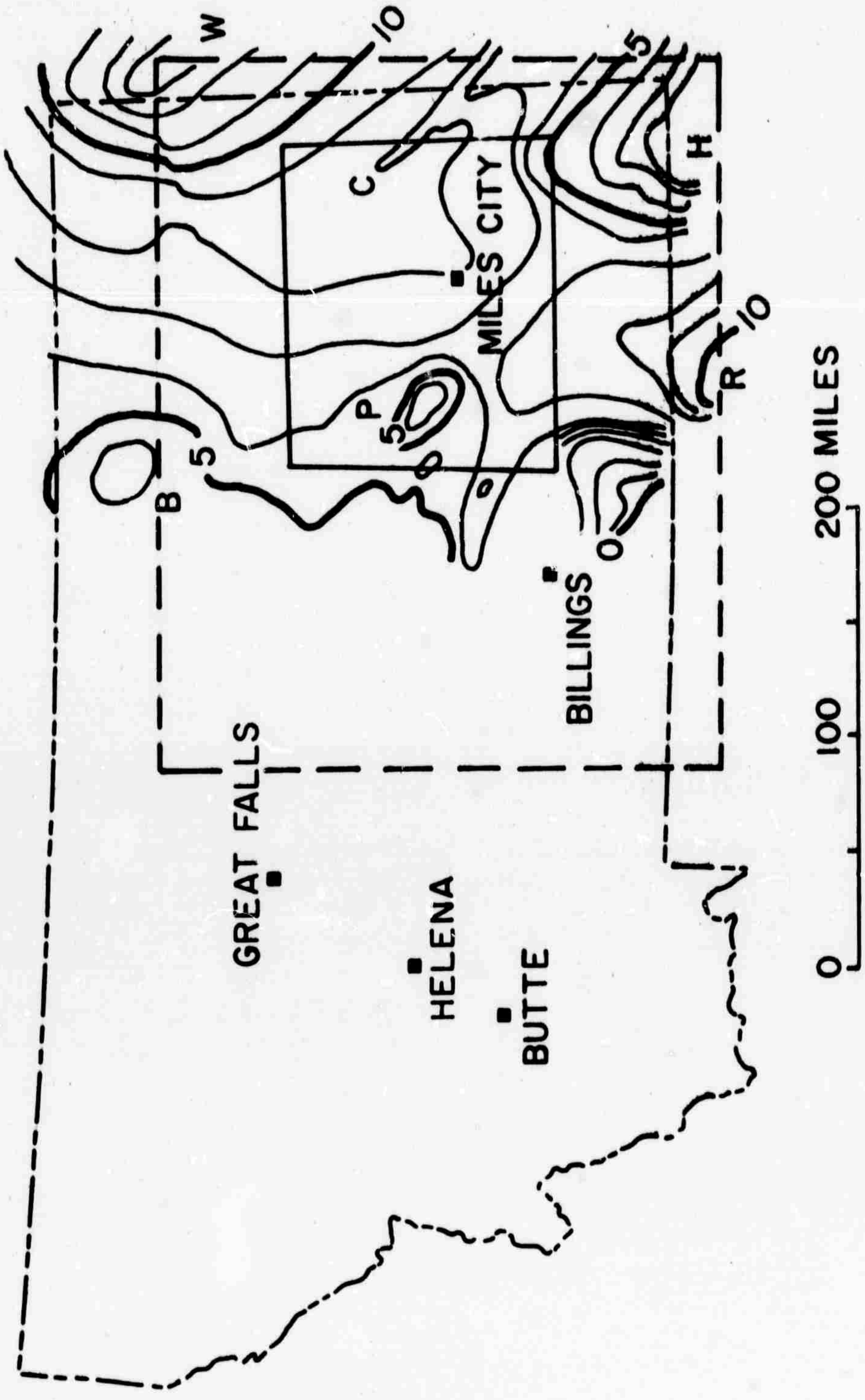

Figure 1. Index map of Montana showing depth to Precambrian basement. Solid line indicates boundary of gravity survey. Dashed line indicates boundary of aeromagnetic survey. Contour interval 1,000 feet. Numbers indicate depths below sea level in thousands of feet. B - Bowdoin dome. C - Cedar Creek anticline. H - Black Hills uplift. P - Porcupine dome. R - Powder River Basin. W - Williston basin.

Figure 2 is in a pocket at the back of this report.

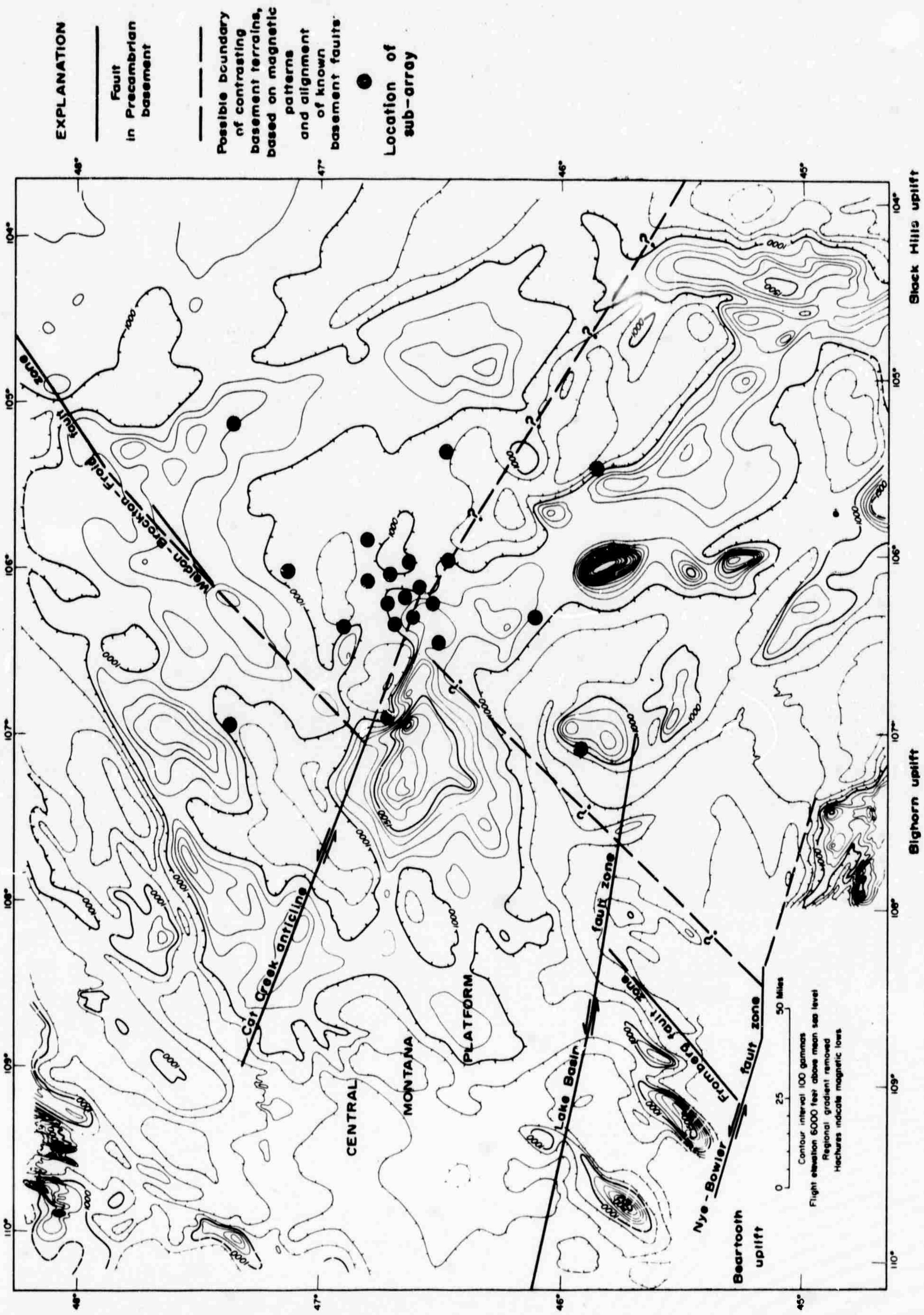

Figure 3. Aeromagnetic map showing major structural trends. Circles indicate location of LASA sub-arrays.

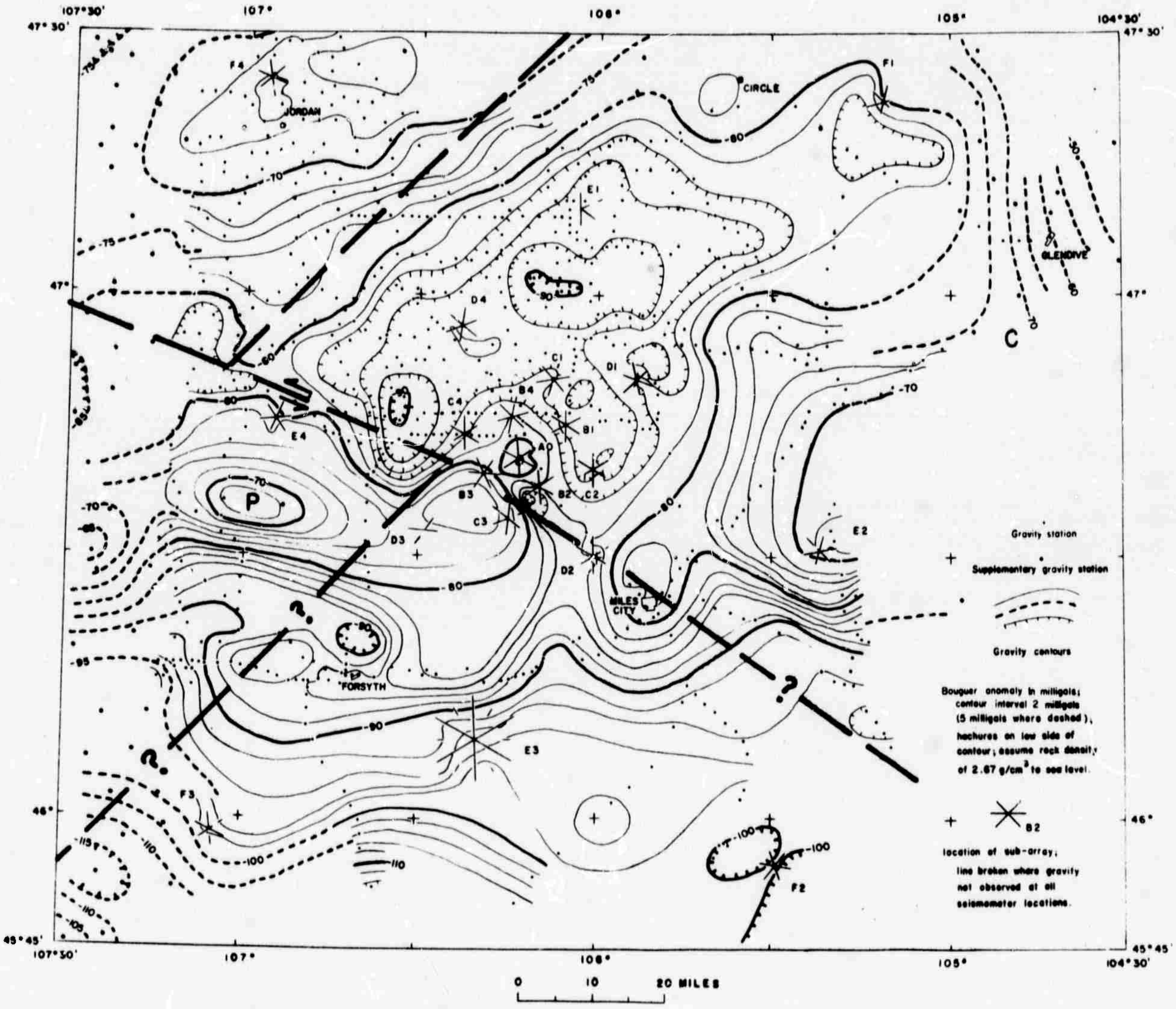

Figure 4. Bouguer-gravity-anomaly map of area near Miles City, Montana.

area of about 16,000 square miles by Donald Plouff, J. E. Carlson, and J. F. Gibbs of the U.S. Geological Survey. The field work was done during parts of June, August, and September, 1967, using LaCoste-Romberg gravity meters G8 and G111. A network of 21 base stations was tied to an absolute datum by locating one of the base stations at a previously established base station, west of the top of the basement stairs north of the Forsyth, Montana, Courthouse. The gravity value there is 980.5088 gals, allowing a 0.02 mgal decrease due to the addition of a 4-inch cement slab since the base was established by Behrendt and Woollard (1961). That value, in turn, agreed to within 0.05 mgal with two ties made to a previously established pendulum station at the Billings, Montana, airport. The accuracy of all observed gravity values probably is better than 0.05 mgal relative to the Forsyth base.

Horizontal control for the gravity survey was obtained from a combination of 1:24,000 scale, 7-1/2-minute, and 1:250,000 scale, one-by-two-degree, maps published by the U.S. Geological Survey and the Army Map Service. The 7-1/2-minute maps were available for about 4,500 square miles of the area. The location accuracy for stations on 7-1/2-minute maps is about 100 feet and for the one-by-two-degree maps errors of about 0.7 mile are probable. Locations provided by LASA-contract surveyors were used for most of the 478 stations established near LASA seismometers.

The elevation control was obtained by establishing gravity stations near 352 U.S. Geological Survey and U.S. Coast and Geodetic

Survey bench marks, near 304 surveyed elevations, and near 13 elevations determined by photo-interpretation methods. Maximum errors expected from these elevations sources are about 1, 2, and 5 feet (0.05, 0.1, and 0.3 mgal), respectively. Elevations provided by LASA-contract surveyors were used for gravity stations established near LASA seismometers. The effect of departures of the ground surface from a flat plane is ignored. The error due to omitting this terrain correction is less than 0.3 mgal.

The Bouguer-gravity-anomaly map (Fig. 4) was supplemented by 60 gravity values from the Department of Defense gravity library. A standard rock density of 2.67 g per cm^3 to sea level was assumed to make the map consistent with the Bouguer-gravity-anomaly map of the United States (1964). Additional detail is shown on Bouguer-gravity-anomaly maps near the various LASA sub-arrays (Figs. 5, 6, 7, and 8).

SUMMARY OF GEOLOGY

The aeromagnetically-surveyed area covers part of the southwestern flank of the Williston Basin, part of the structurally complex area of central Montana, the northern parts of the Black Hills uplift, the Powder River Basin, the Bighorn Mountains uplift, the Bighorn Basin, and the Beartooth Mountains uplift, and it extends northward to the Bearpaw and Little Rocky Mountains uplifts (Fig. 9). The area is underlain by as much as 15,000 feet of sedimentary rocks of Paleozoic to Paleocene age above a basement of crystalline rocks of pre-Belt Precambrian age, except on the western edge, in the area of the central Montana uplift, where the Precambrian Belt

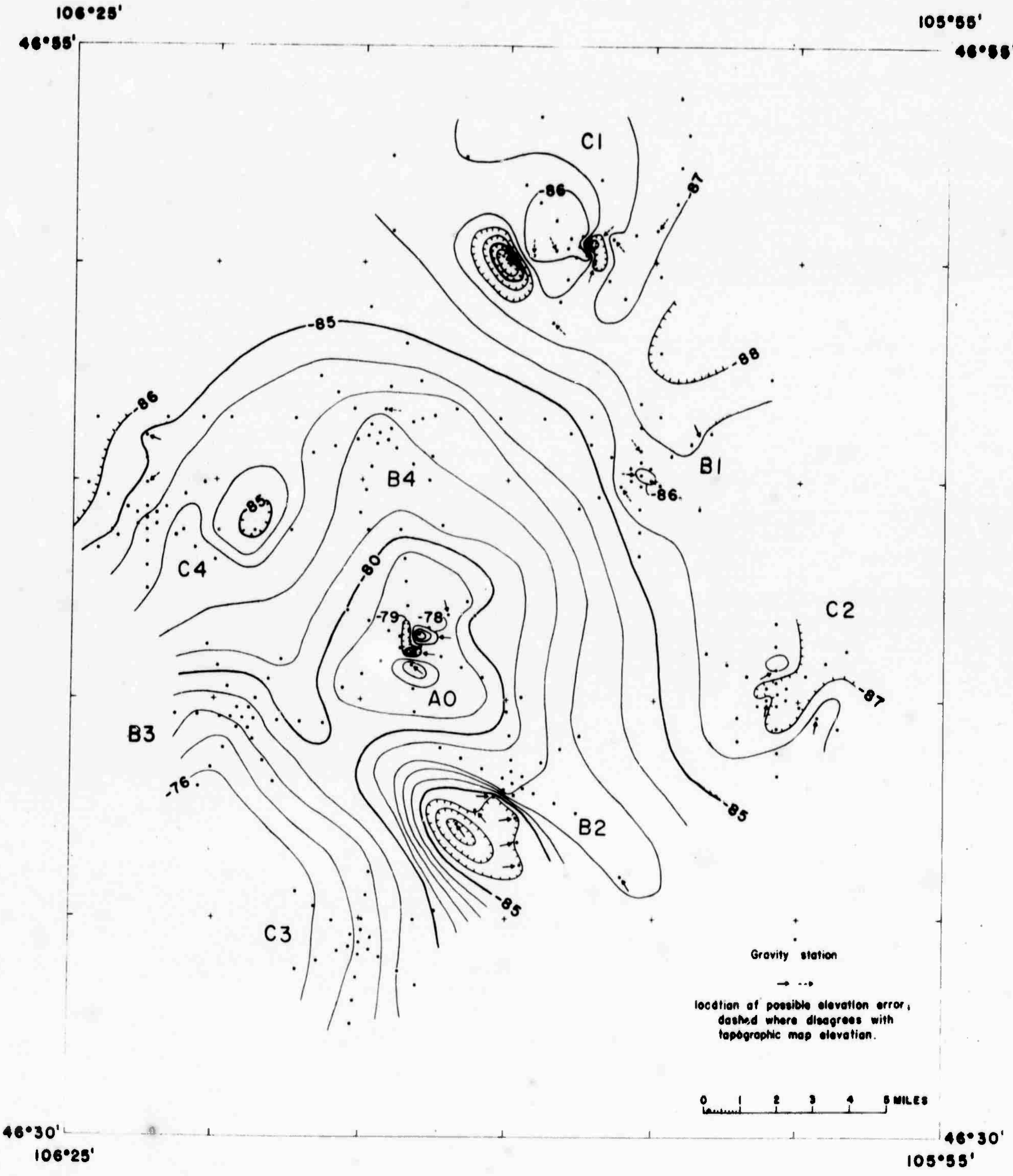

Figure 5. Bouguer-gravity-anomaly map, inner sites of LASA array.

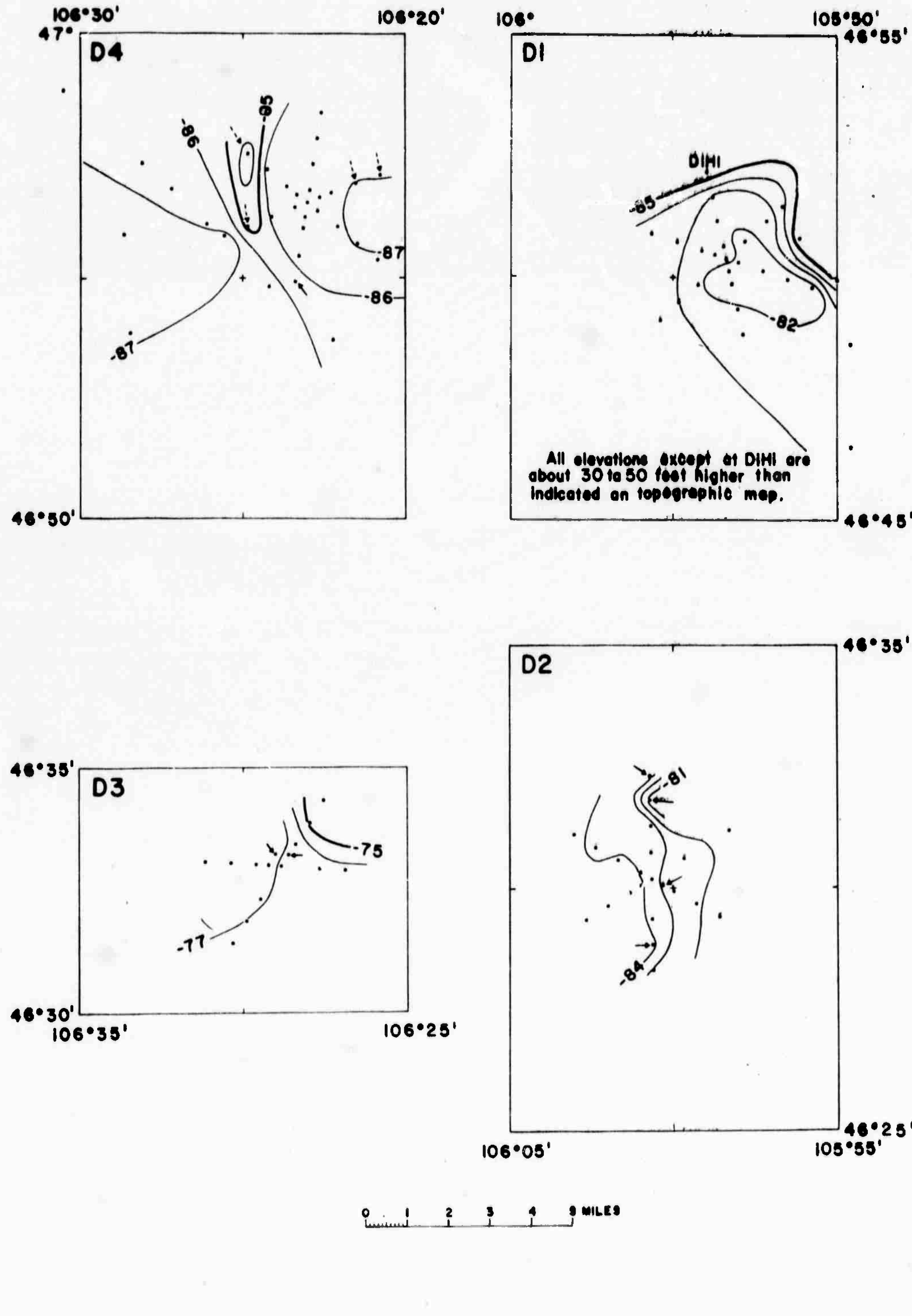

Figure 6. Bouguer-gravity-anomaly map, D-ring of LASA array.

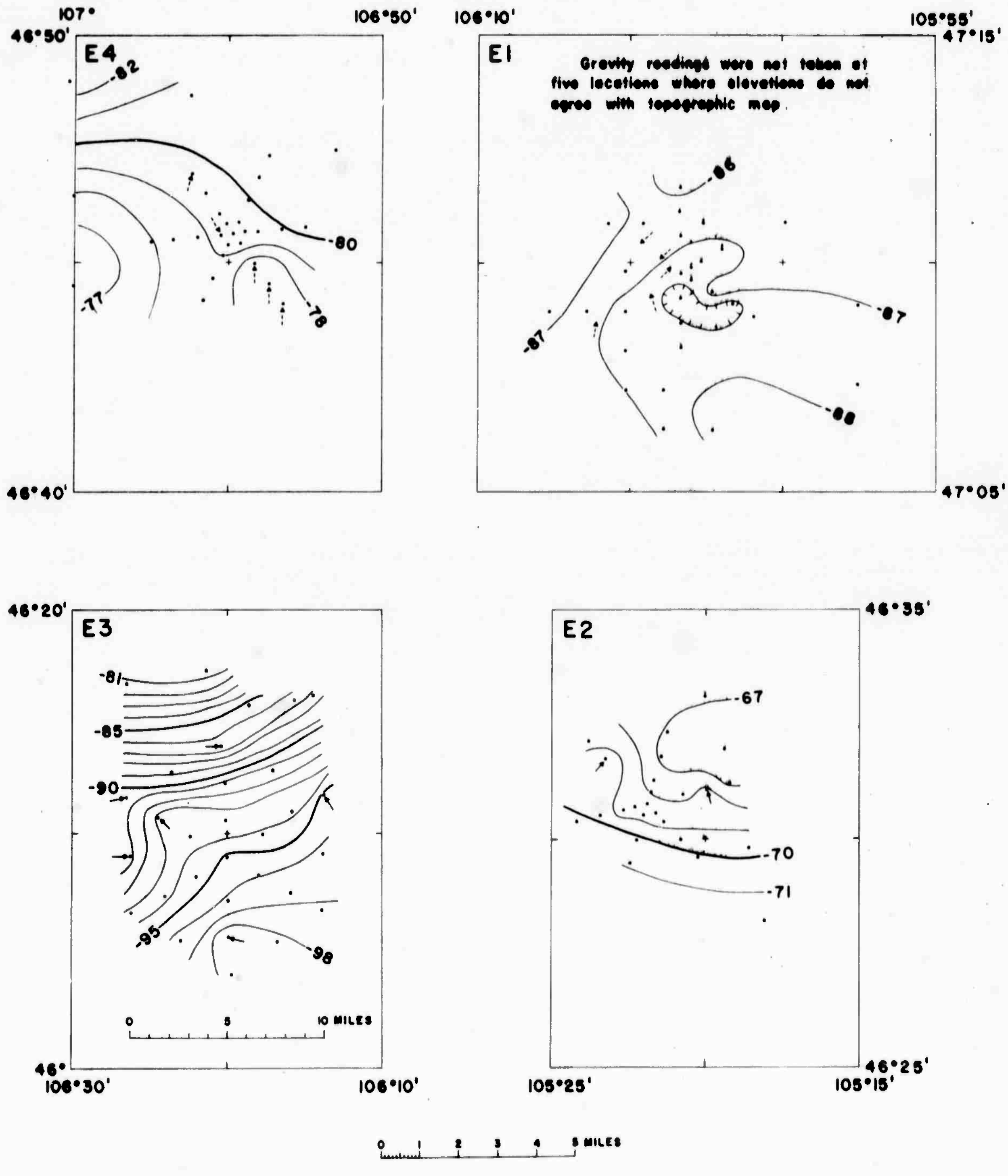

Figure 7. Bouguer-gravity-anomaly map, E-ring of LASA array.

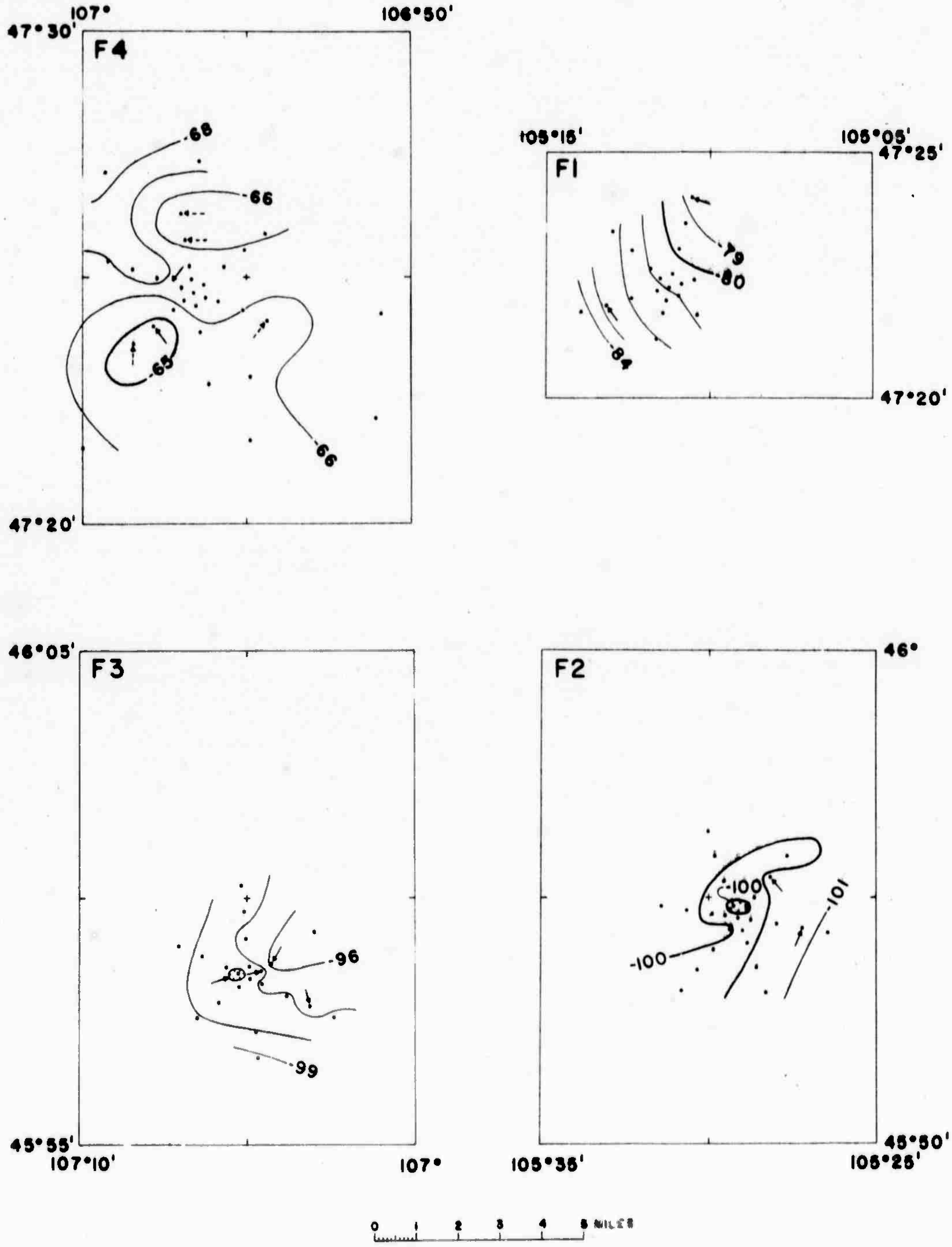

Figure 8. Bouguer-gravity-anomaly map, F-ring of LASA array.

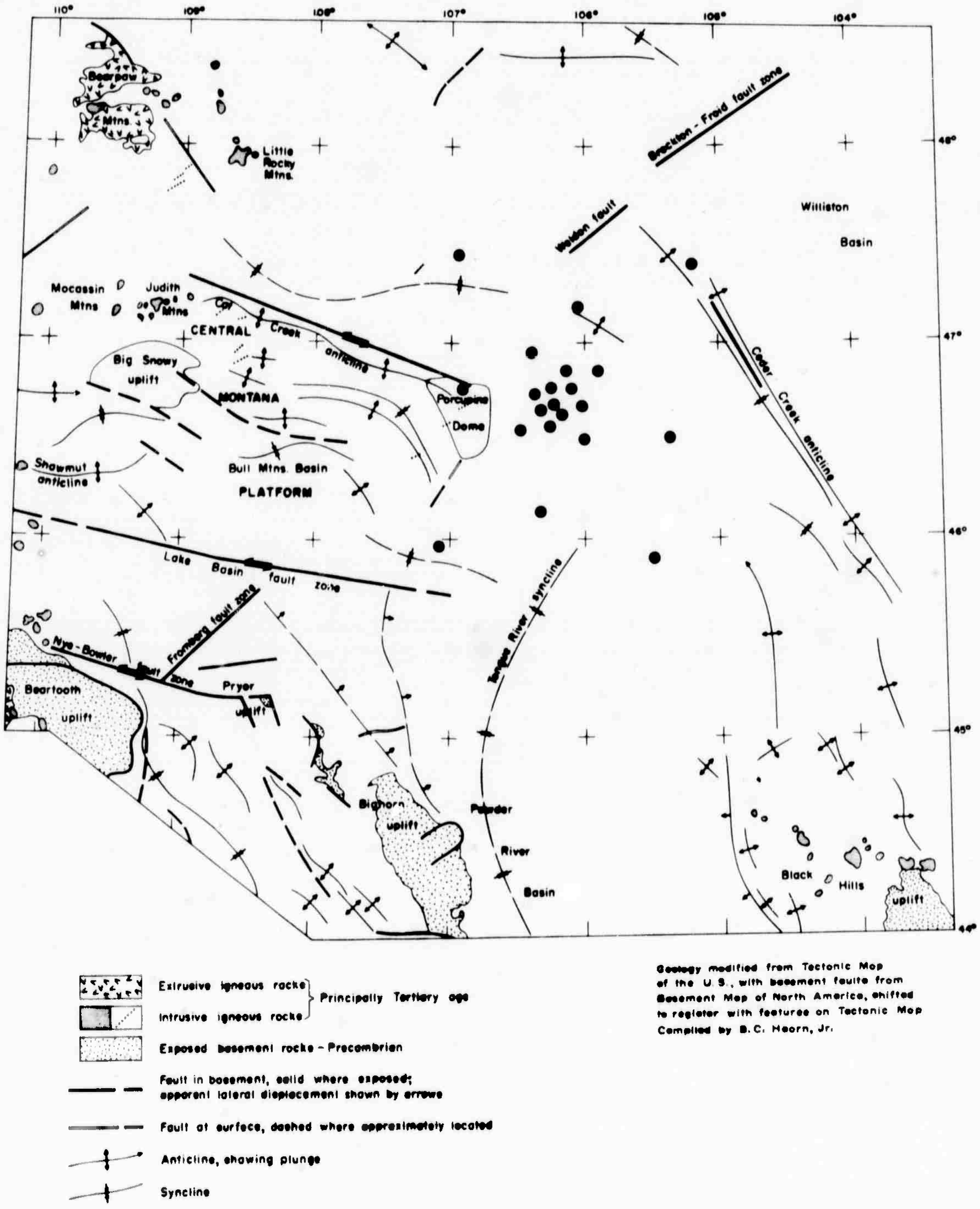

Figure 9. Tectonic map of eastern Montana.

Series overlies the crystalline basement (Harris, 1957; Sloss, 1950). The crystalline basement is exposed only in mountain uplifts on the periphery of the area. In the central part the unexposed crystalline basement has been penetrated by sixteen drill holes.

The structural complexity of the Paleozoic and younger formations in central and eastern Montana is generally considered to be the result of two processes: differential movement of fault blocks in the crystalline basement (Thom, 1923; Sonnenberg, 1956; Norwood, 1965) and intrusion of igneous rocks, principally of Tertiary age. Isopach and lithofacies maps of formations above the basement show that movement on many of the basement faults has been recurrent. The basement faults are thought to be reactivated structures, or zones of weakness, of Precambrian age. Within that context, the aeromagnetic patterns, and to some extent the gravity patterns, show a marked correlation with known basement structures and suggest other structural trends and lithologic variations within the buried basement.

INTERPRETATION

As the major long-wavelength magnetic anomalies do not correspond with sharp circular uplifts typical of Tertiary intrusive areas in the plains, they are not likely to be indicative of Tertiary intrusions at depth, and can most likely be attributed to differences in Precambrian lithology within the crystalline basement. The magnitude of the major aeromagnetic and gravity anomalies is too great to be explained by relief on the basement surface, with the

exception of the aeromagnetic anomalies over the Beartooth uplift. Anomalies of high magnitude and sharp gradient are due to comparatively shallow features, whereas anomalies of smaller magnitude and more gentle gradient may be due to either greater depth, or to smaller magnetic intensity or density contrast of bodies at shallow depth. Elongate anomalies of gentle gradient could be due to elongate Precambrian intrusions, or to metamorphic rocks of differing magnetic intensity or density contrast; in either case, the elongation is probably indicative of structural trends within the basement. The small-scale, sharp variations in magnetic intensity in the Bearpaw, Little Rocky and Judith Mountains are due to Tertiary instrusive and extrusive rocks.

The magnitudes of strong anomalies are, in general, compatible with mafic igneous bodies, and are greater than expected for felsic igneous rocks in Precambrian metamorphic terrain. Anomalously-high values of gravity would be expected over mafic bodies surrounded by felsic rock, and the values of gravity would be expected to decrease as the thickness of the sedimentary section increases, inasmuch as the average density of sedimentary rocks is low compared to the density of crystalline basement rocks. The values of the magnetic field similarly would decrease, inasmuch as the sedimentary rocks are generally nonmagnetic.

<u>Black Hills uplift</u> -- The northern flank of the Black Hills uplift (Fig. 9) is underlain by a magnetic high which bifurcates northward, into two magnetic ridges of northwest and north trend.

These trends are parallel to the known structures in the Paleozoic and younger formations on the northern flank of the uplift, and parallel to the structures in the exposed Precambrian rocks in the uplift.

Cedar Creek anticline -- This major structure in the Williston basin is a sharp anticlinal fold whose steep west limb overlies a recurrent fault in the basement (Sandberg, 1962). The anticline is associated with a magnetic high offset toward the southwest. The gravity effect is a small high near Circle, Montana, and a saddle to the southeast that interrupts a major gravity low to the southwest.

Tongue River syncline -- The main anomalies in the vicinity of the Tongue River syncline have no known corresponding structure above the basement, and are most likely due to plutons of Precambrian age within the basement. The gravity high at latitude 46° and longitude 106° is located near the northernmost of a series of magnetic highs.

Weldon fault and Brockton-Froid fault zone -- The Brockton-Froid fault zone, which is known to extend into the basement, offsets Pleistocene deposits and thus shows the youngest known fault activity in eastern Montana. The Weldon fault has been recurrently active and may also extend into the basement (Sandberg, 1962). The gravity gradient distinctly shows that the fault zone forms the northwest boundary of a large block of relatively-low-density material to the southeast. The zone also appears to be the approximate locus of a change from weak northwest to strong northeast magnetic trends corresponding to structure within the basement.

Central Montana uplift-Central Montana platform -- The central Montana uplift, or central Montana platform (Sonnenberg, 1956), an east-southeast trending band of domes and folds which is approximately coincident with an ancestral uplift and the western part of the depositional trough of central Montana, is the locus of recurrent vertical movement of basement blocks. The recurrent tectonic activity has had a profound effect on deposition of sedimentary rocks, from a time possibly as early as Beltian Precambrian until lower Cretaceous time (Sloss, 1950; Norwood, 1965). Within the map area, the uplift is bounded on the north by the Cat Creek anticline, a sharp flexure which overlies a fault in the basement, and is bounded on the south less distinctly by the eastward continuation of the Devils Basin and Big Wall anticlinal trend. The central Montana platform may include the genetically related Bull Mountains Basin (Sonnenberg, 1956) and thus could be considered to be bounded on the south by the Lake Basin fault zone. The eastern limit of the central Montana uplift or platform variously includes or excludes the problematical Porcupine Dome, depending on whether the dome is related to a subjacent Tertiary intrusion (Thom, 1923; Reeves, 1927; Norwood, 1965) or to basement faulting (Staggs, 1956; Harris, 1957).

The Tertiary igenous rocks of the Judith and Mocassin Mountains have only a superficial magnetic effect and are not apparently underlain by major magnetic plutons in the basement. The Big Snowy uplift shows no strong magnetic contrast in basement lithology across the basement fault on its south border, and thus was not produced

by a major magnetic pluton in the basement.

Porcupine Dome -- The wide irregular magnetic anomaly situated near the eastern edge of the central Montana uplift suggests that a pluton in the basement is bounded in part by the same basement features which delineate the uplift. The east-southeast orientation of the eastern end of the anomaly indicates that, in terms of basement contrast, the Cat Creek trend extends eastward beyond any apparent structural effect in the overlying rocks. A pronounced gravity high corresponds to the magnetic high, and has a similar prolongation to the east-southeast. The gravity data favor a mafic composition for the postulated pluton. The geophysical data, coupled with the absence of igneous rocks intruding the sedimentary section in a drill hole in the center of the dome, and the known relief of the basement surface beneath the dome, suggest a fault-produced rather than an igneous origin for Porcupine Dome. The alignment of sparse thin mafic dikes of Tertiary age on and southwest of Porcupine Dome is individually east-northeast, but as a group is northeast, and may be related to a basement feature responsible for the northeast-trending boundary of the Porcupine Dome magnetic anomaly.

Lake Basin fault zone -- This major lineament is a zone of left-lateral en echelon faults with as much as 2500 feet of vertical displacement. The fault as shown on the Basement Map of North America (AAPG and USGS, 1967) extends beyond the limits of faulting at the surface. The magnetic data show that the Lake Basin fault zone occurs

along a pronounced change in apparent structure, but does not establish lateral displacement along the basement fault.

Fromberg fault zone -- This zone, which consists of a long narrow graben at the surface and is underlain by a basement fault, appears to mark the southeastern limit of basement terrain with strong northeast trending magnetic anomalies in the structural block between the Lake Basin and Nye-Bowler fault zones.

Nye-Bowler lineament -- The Nye-Bowler lineament, a zone of faults, in part en echelon, shows some left-lateral movement but the main displacement has been vertical; the zone is underlain by a basement fault which extends eastward beneath the Pryor Mountains uplift. The magnetic data (Figs. 2 and 3 and Balsley and others, 1948) indicate that a line of major contrast in basement lithology follows the Nye-Bowler lineament beneath the Pryor Mountains uplift, and can be extended eastward to the northern end of the Bighorn Mountains uplift. Thus, the magnetic data support the contention of Foose and others (1961), on the basis of gravity data over the Nye-Bowler zone, that "there are fundamental differences in the lithology and structure of the deep basement adjacent to this zone."

MAJOR FEATURES OF THE AEROMAGNETIC AND GRAVITY MAPS

The aeromagnetic and gravity maps suggest that several linear fault zones at the surface, that extend into the Precambrian basement, define boundaries between terrains of differing structure, lithology, and abundance of plutons in the Precambrian basement. The structural features are the three major east-southeast trending lineaments of

central Montana, the northeast trending Brockton-Froid and Weldon fault line of northeast Montana, and another possible feature which would extend from the northeast flank of the Black Hills uplift to the east side of Porcupine dome, but which is marked only by an unnamed arch at the surface (Fig. 9). The latter feature may be the division between the relatively simple structure of supra-basement formations in the plains to the northeast, and the more complex structure of such formations to the southwest, and marks the eastern limit of known occurrences of Tertiary igneous rocks. To the northeast of the northwest trending line, anomalies are widely spaced and of gentle gradient; strongly magnetic plutons appear to be absent. West of the line, there are numerous moderate to strong aeromagnetic anomalies, with several preferred orientations, interspersed with areas of gentle magnetic gradient. The line of structural contrast may terminate northwestward, or may be offset to the northeast, in the vicinity of Porcupine dome.

A northwesterly trend of both the magnetic anomaly and the axis of the Cedar Creek anticline appears to end approximately along the line of the Brockton-Froid fault zone and Weldon fault, northwest and west of which the trend of the magnetic anomaly, the gravity anomaly, and the assumed structural grain of the basement is markedly northeast. A northeast magnetic grain is similarly pronounced in the structural province between the Lake Basin and Nye-Bowler fault zone, but is only weakly expressed in the magnetic pattern in the intervening structural province of the Central Montana uplift or platform.

South of the Nye-Bowler fault zone, the predominant magnetic grain is northwest.

Another line of junction of northeast trending and north- to northwest-trending magnetic patterns of basement rocks could be drawn approximately from the Pryor uplift through the southeast flank of the Porcupine Dome. Such a line would be parallel to, but offset from, the Brockton-Froid-Weldon fault line. It does not coincide with known major fault structures at the surface or in the basement.

The high over Porcupine Dome and the major low to the northeast of the Cat Creek zone are the most prominent features on the gravity map. The effect of 3,000 feet of thinning of the sedimentary section over Porcupine Dome contributes only slightly to the gradient at the boundary. The gravity low corresponds to a wedge-shaped mass of probably felsitic rock that thickens to the southwest until truncated by the more dense mafic rock underlying Porcupine Dome.

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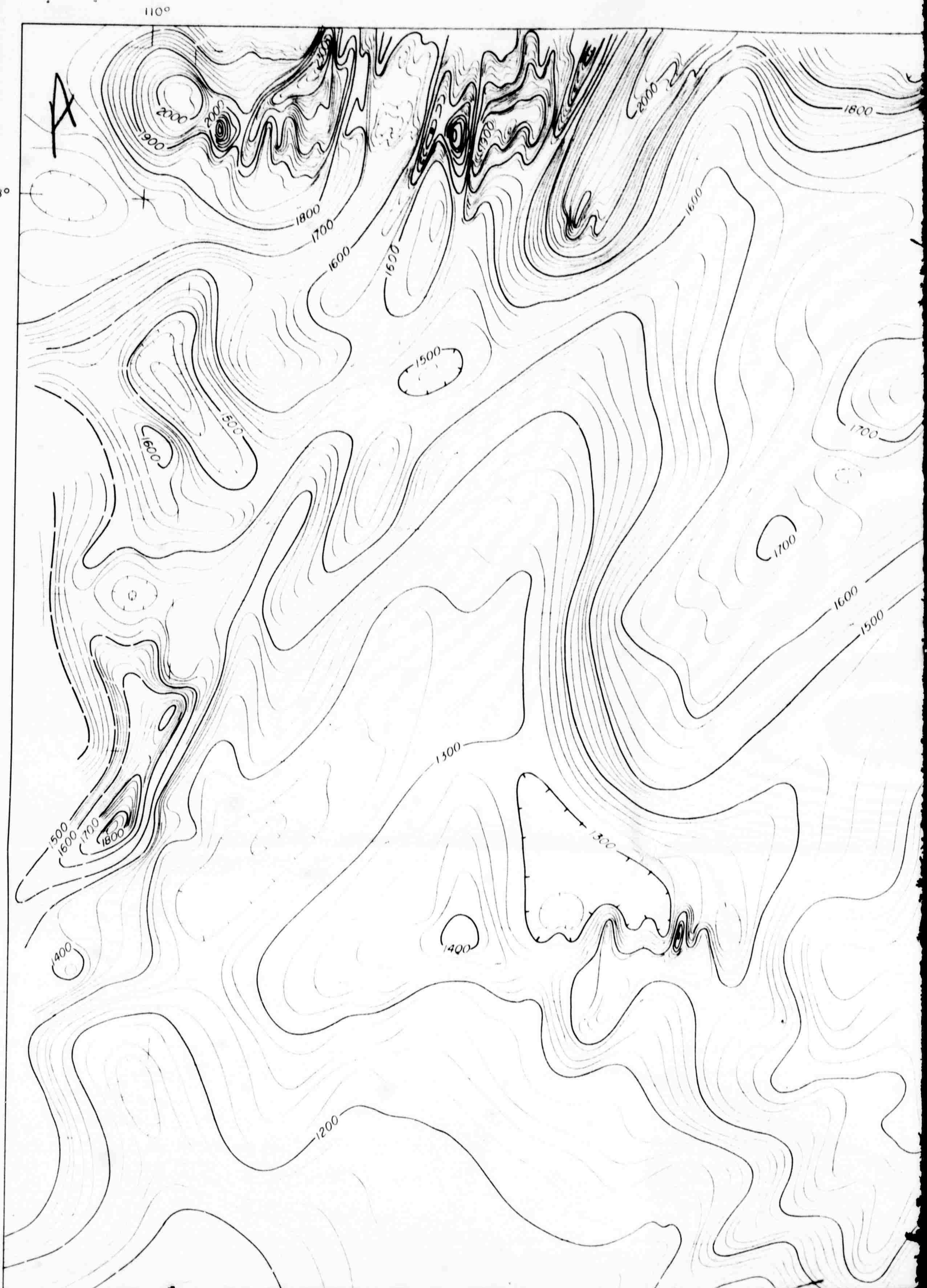
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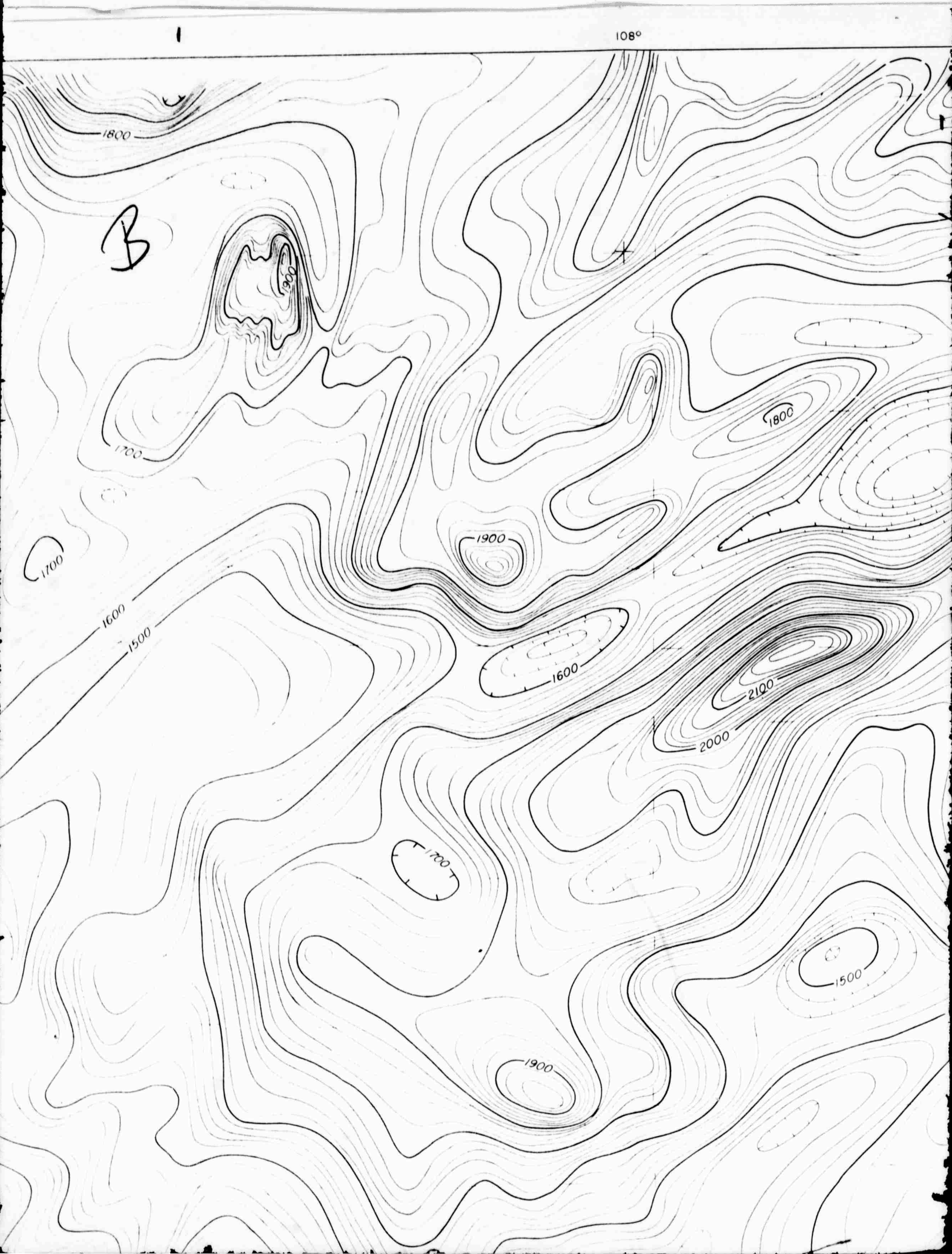

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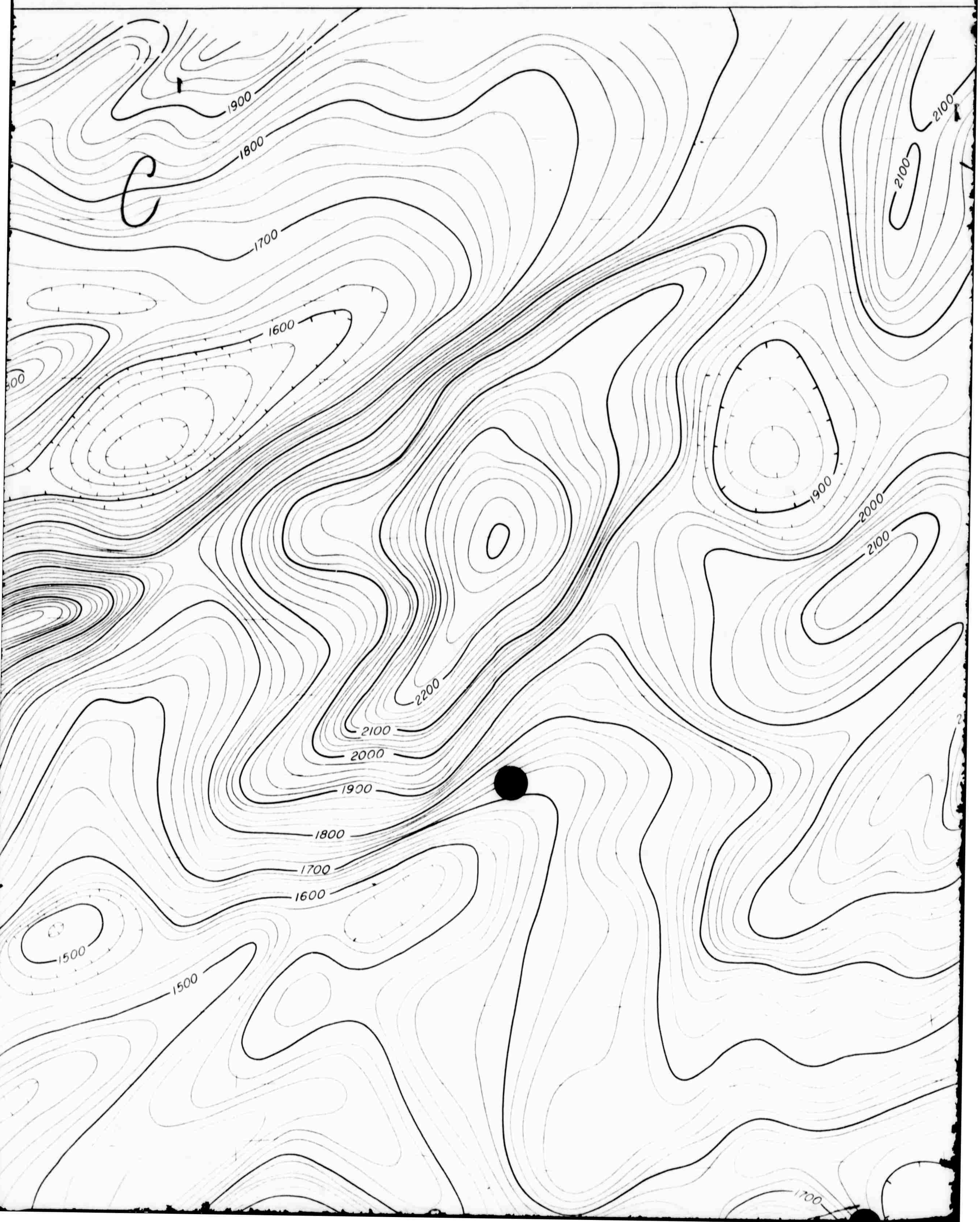

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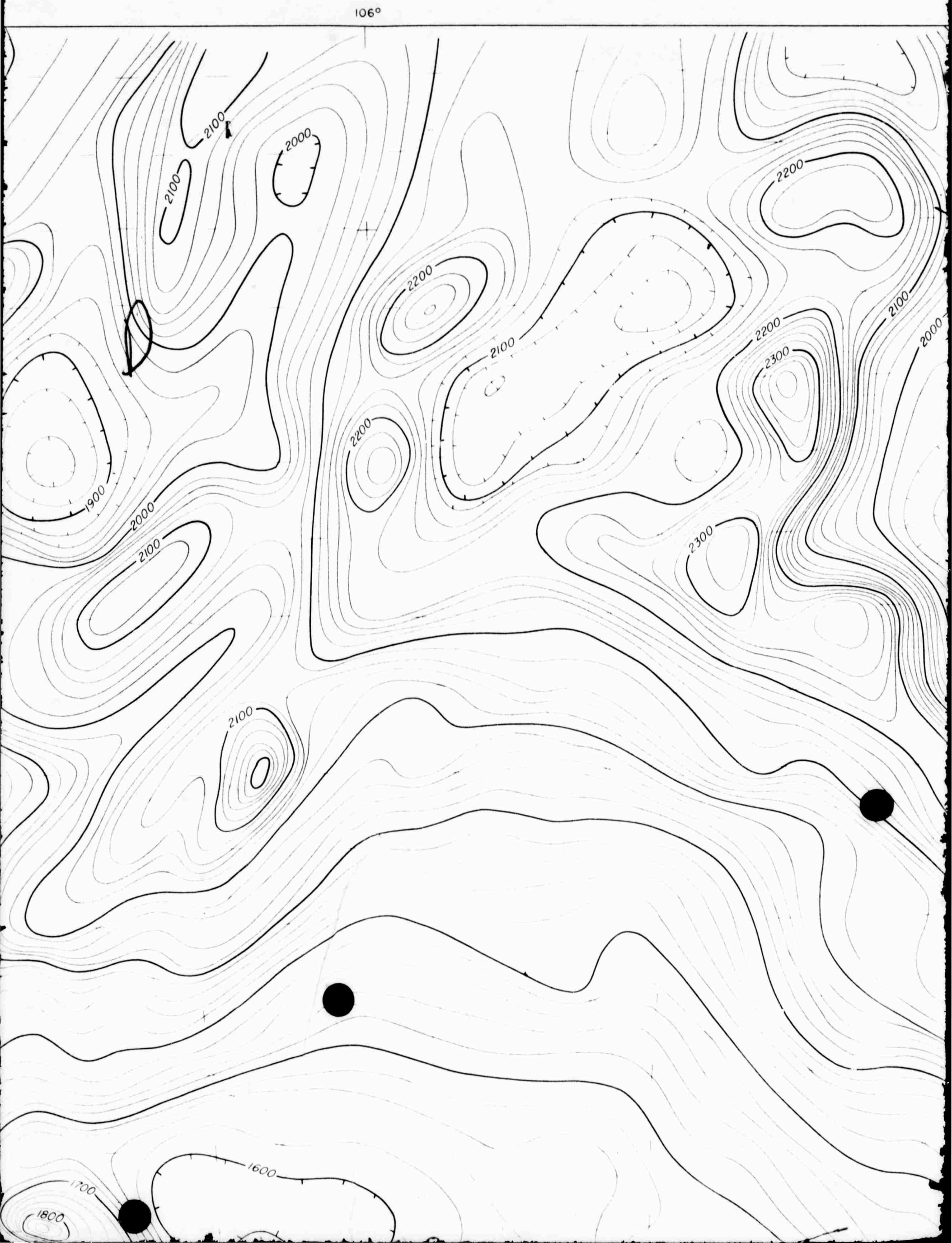
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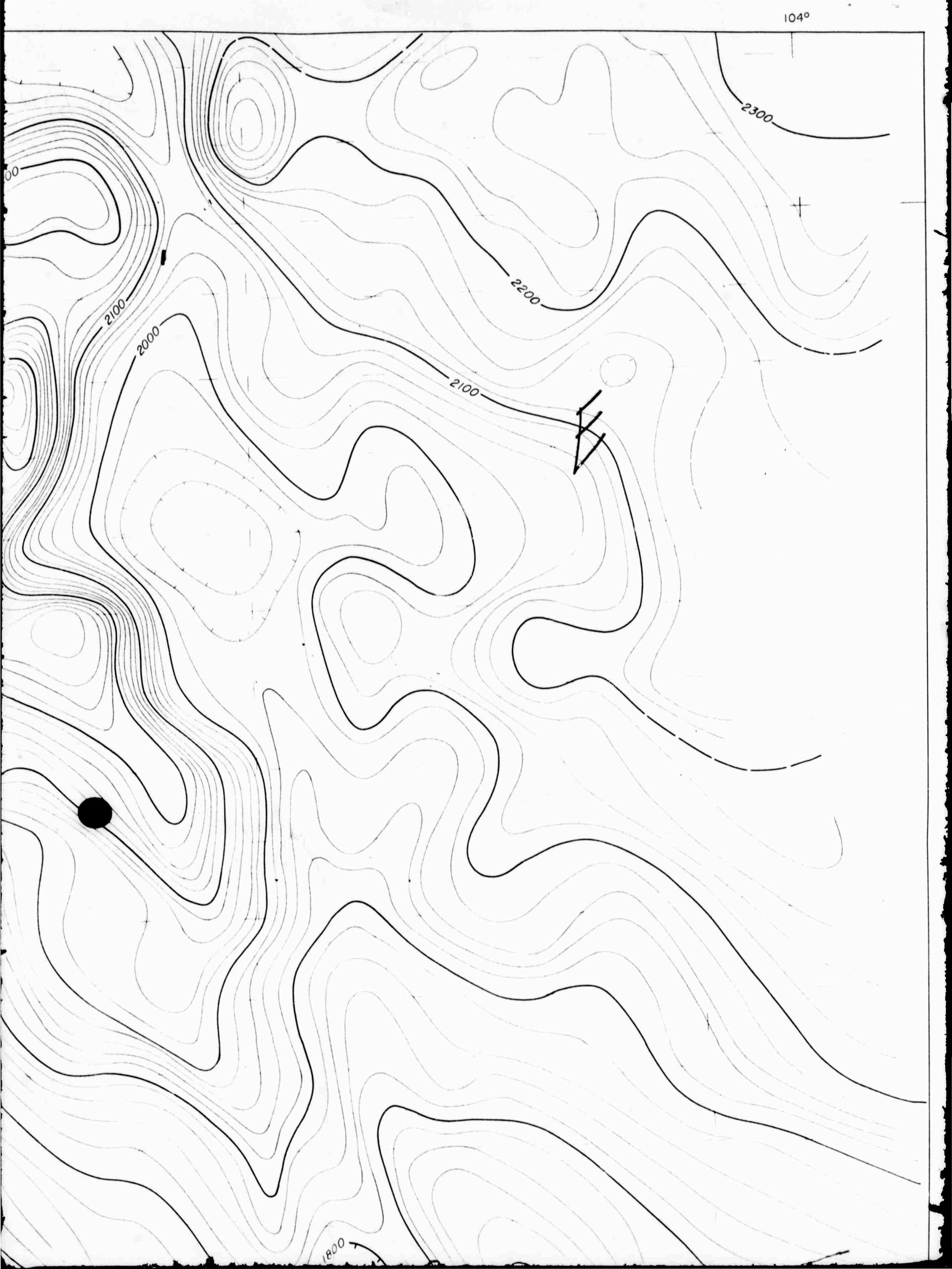
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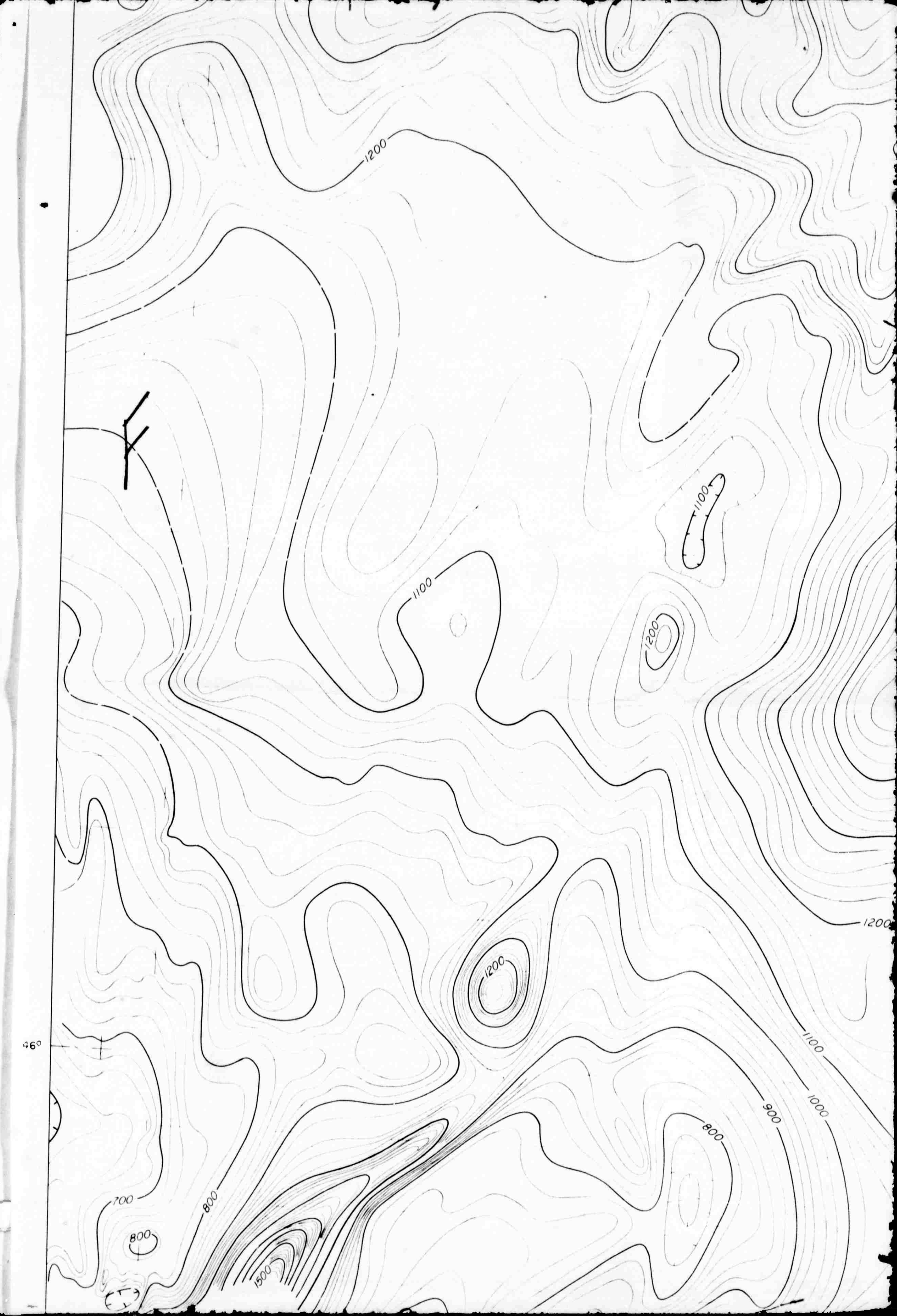
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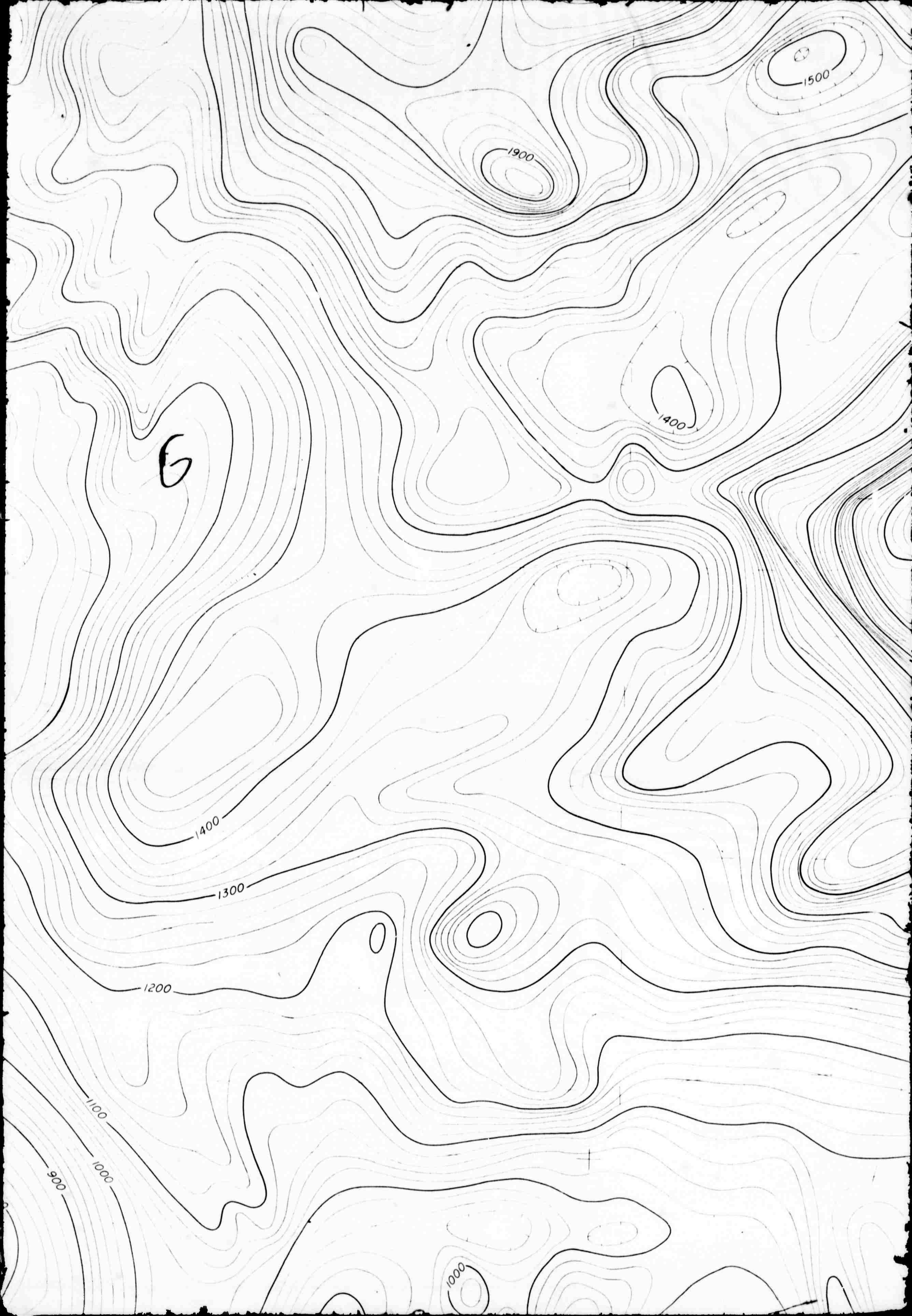
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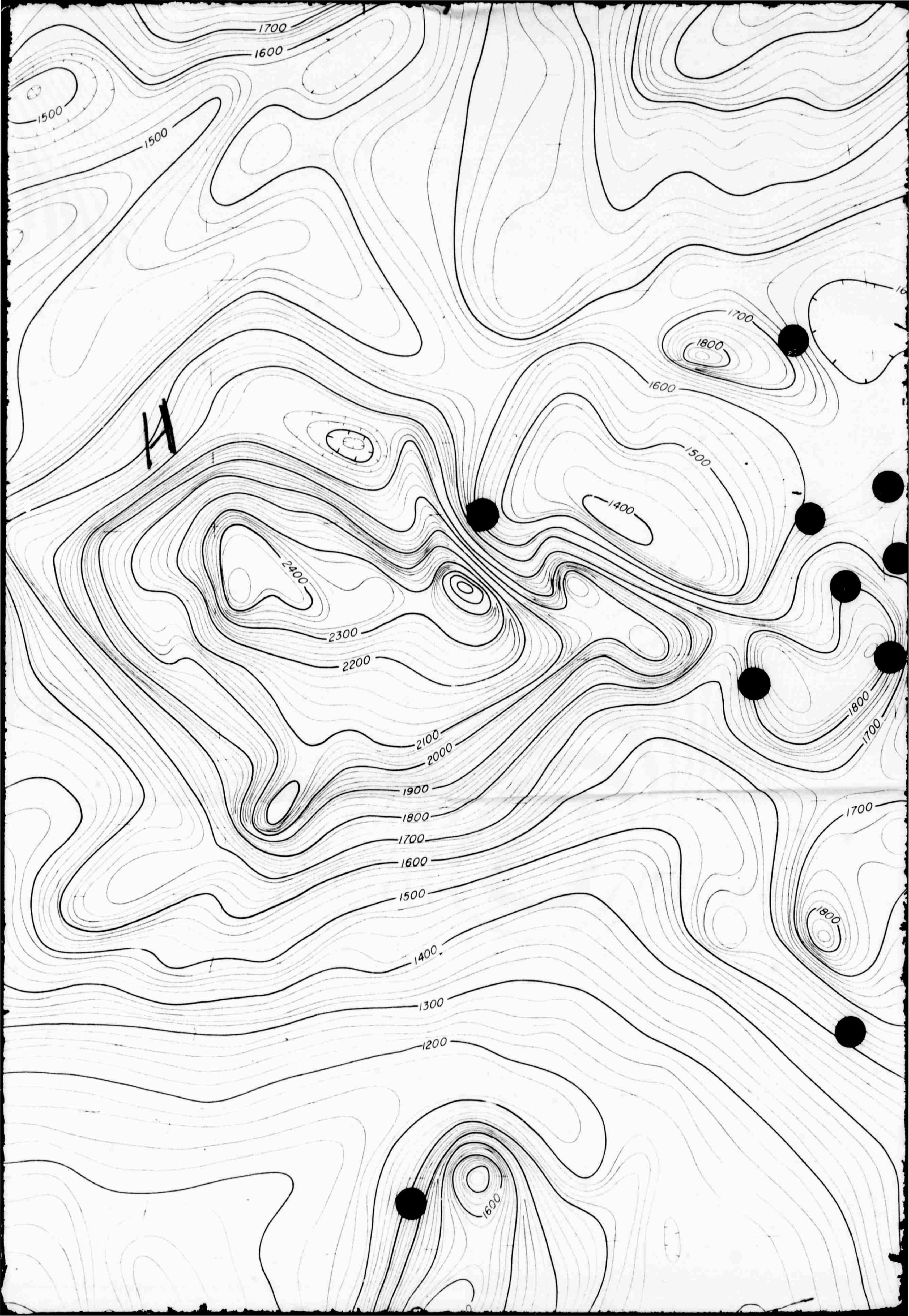

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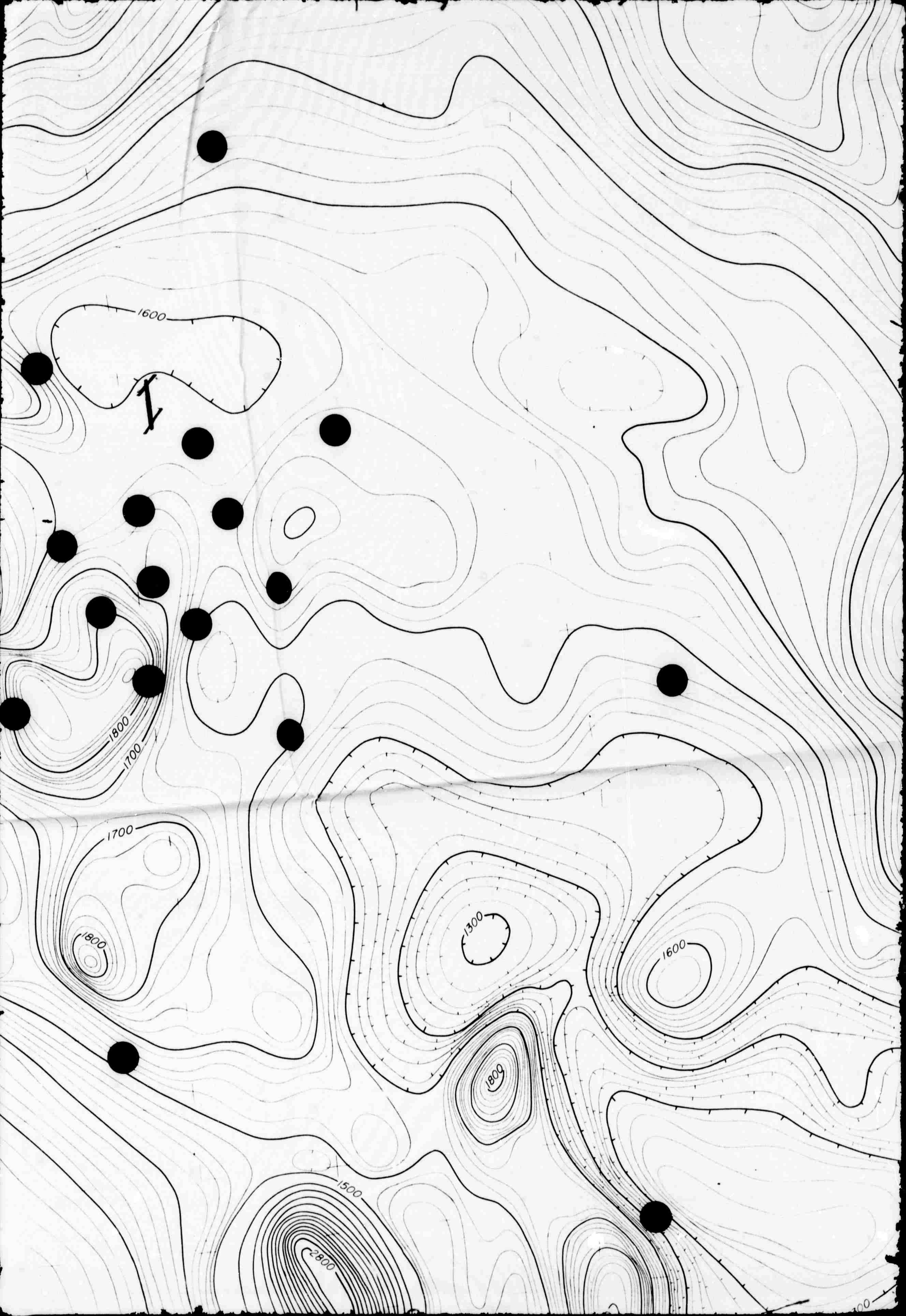

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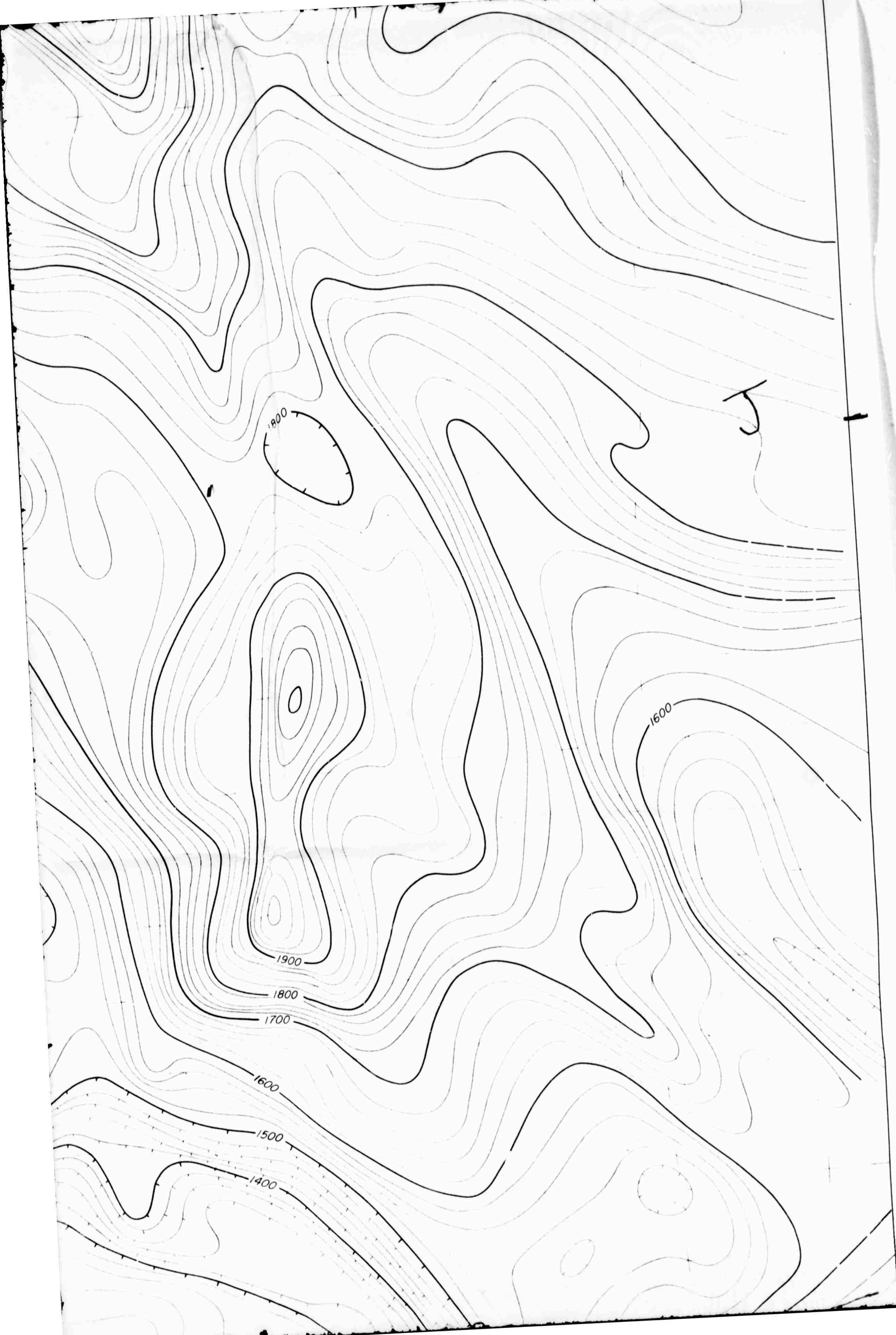
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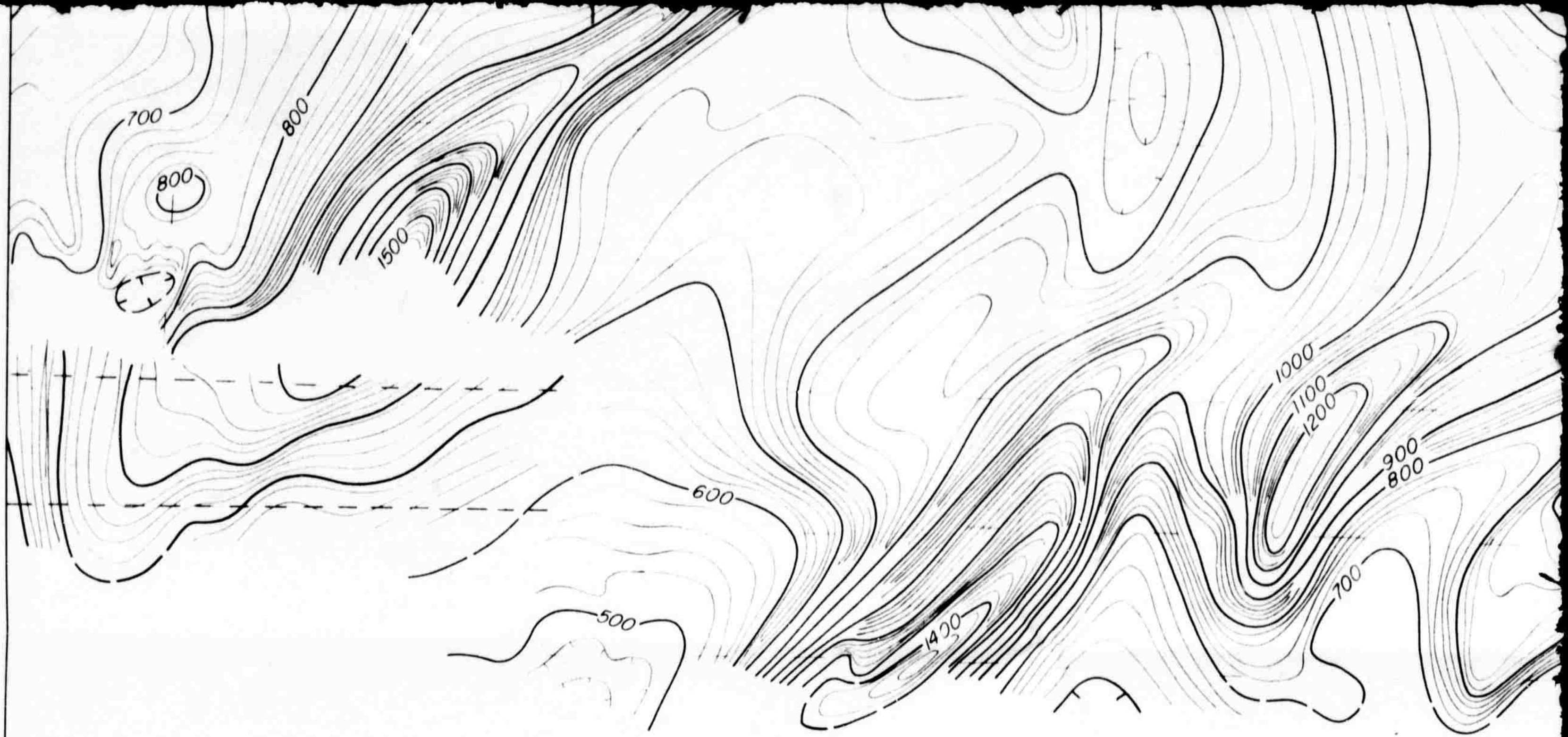

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Contour interval 20 and 100 gammas
Flight elevation 6000 feet above mean sea level
Magnetic contours of total intensity relative to arbitrary datum
Hachures indicate magnetic lows

Location of LASA sub-array

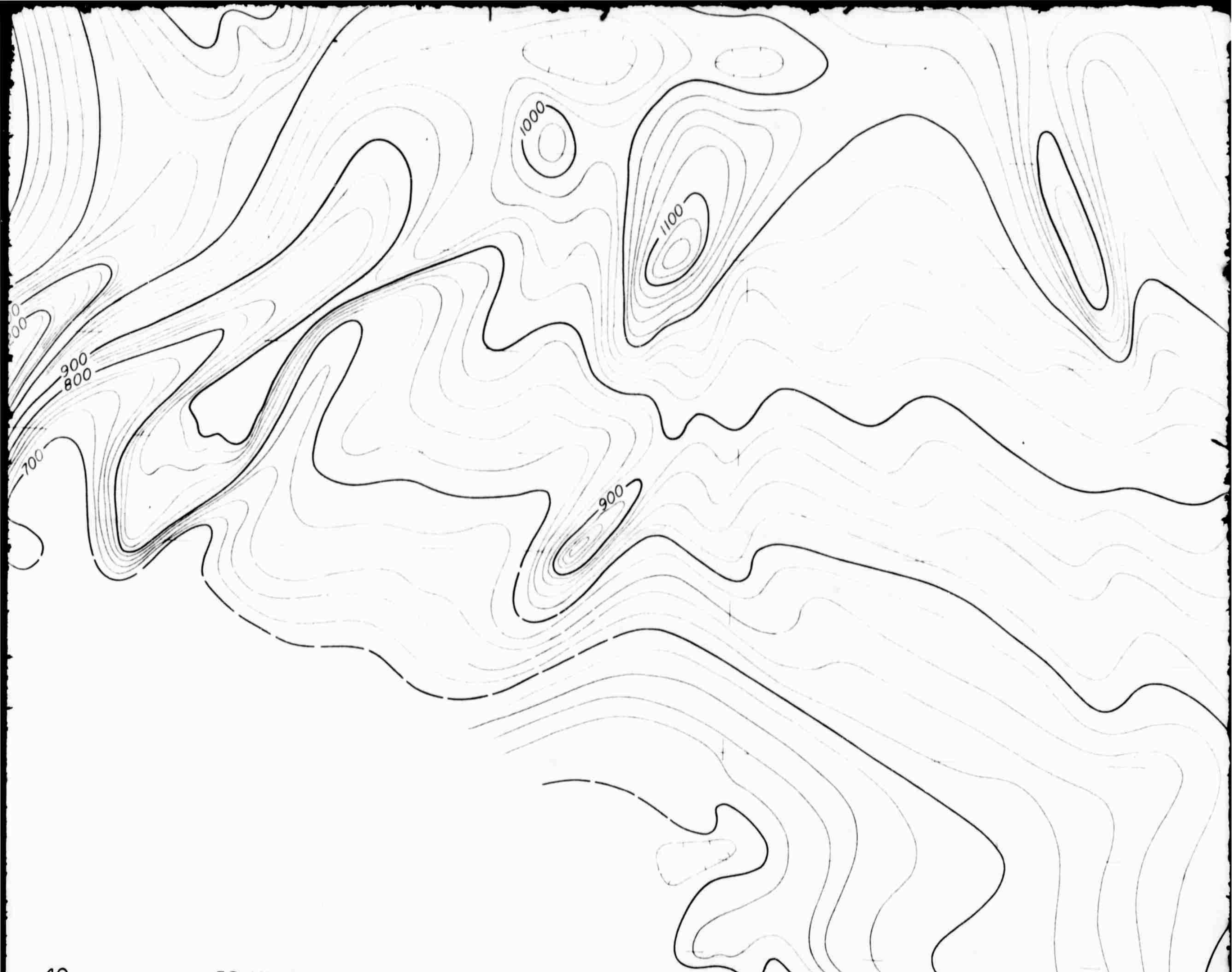

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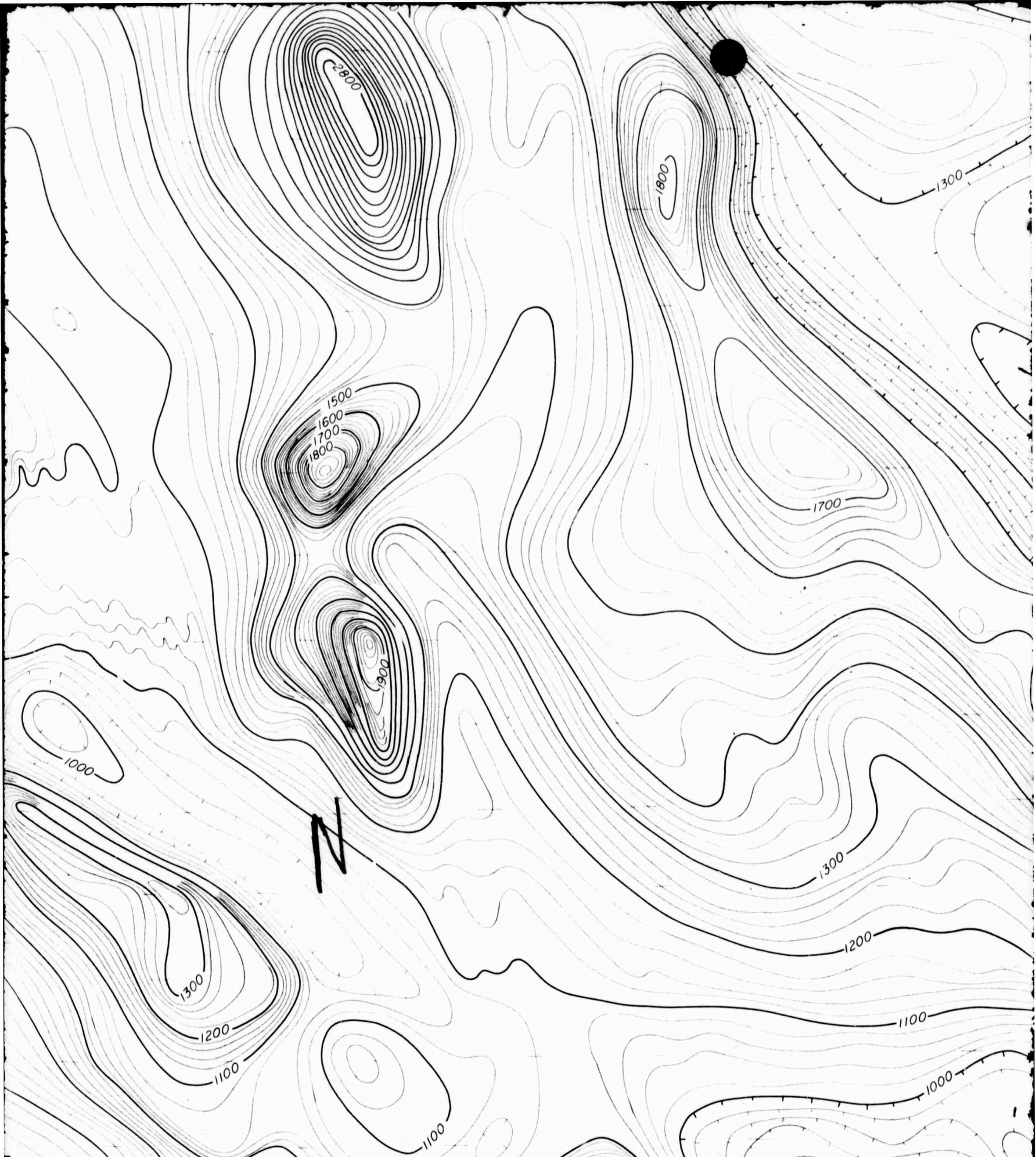
FIGURE 2. AE

FIGURE 2. AEROMAGNETIC MAP OF EASTERN MONTANA



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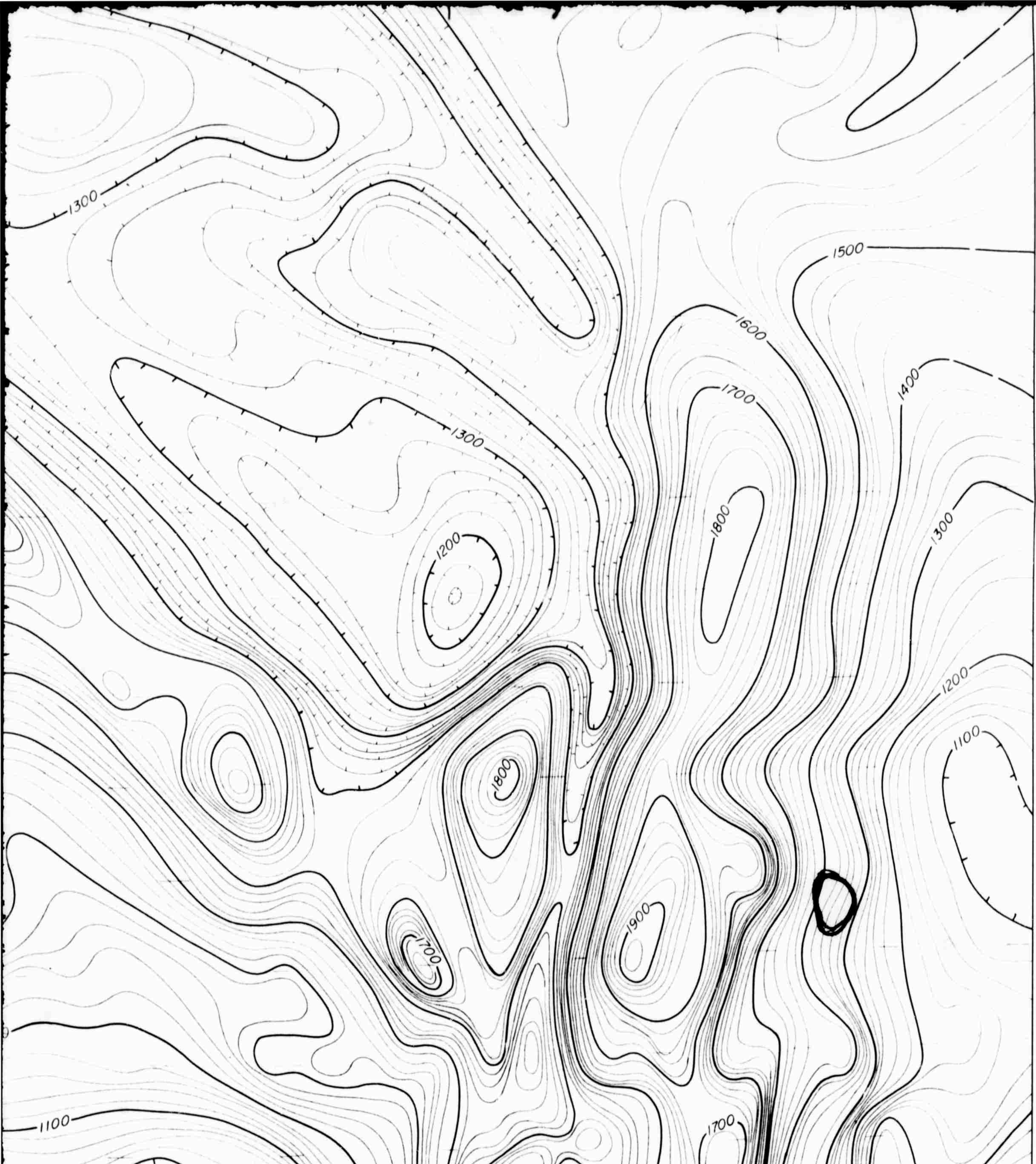
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